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Effect of Surface Treatments on Electron Beam Freeform Fabricated Aluminum Structures

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Abstract

Electron beam freeform fabrication (EBF³) parts exhibit a ridged surface finish typical of many layer-additive processes. Thus, post-processing is required to produce a net shape with a smooth surface finish. High speed milling, wire electrical discharge machining (EDM), electron beam glazing, and glass bead blasting were performed on EBF³-built 2219 aluminum alloy parts to reduce or eliminate the ridged surface features. Surface roughness, surface residual stress state, and microstructural characteristics were examined for each of the different surface treatments to assess the quality and effect of the surface treatments on the underlying material. The analysis evaluated the effectiveness of the different surface finishing techniques for achieving a smooth surface finish on an electron beam freeform fabricated part.

Introduction

The electron beam freeform fabrication (EBF³) process has been developed over the past two years at NASA Langley Research Center. A computer model of a component is created and translated into programmable machine code for driving the EBF³ system. A focused electron beam is used to create a molten pool on a metal substrate. Wire is fed into the molten pool and the substrate is translated with respect to the electron beam and wire to build a layer. The final part is, thus, built up layer by layer. However, as with many layer-additive processes, the surface exhibits a ridged surface finish corresponding to the deposited layers. If the component is designed to be built as a near-net shaped part in the freeform fabrication system, then some form of post-processing is planned as part of the manufacturing life cycle to achieve final dimensional tolerance and adequate surface finish for the intended application. In this case, as long as the surface finish is conducive to performing secondary machining, (i.e. the ridges in the surface do not induce chatter or otherwise impact the performance of the tool), then the surface finish is not a significant issue. However, for other applications, it is desirable to achieve final dimensions and surface finish directly from the fabrication process. To accomplish production of net-shaped parts directly in the EBF³ system, techniques need to be developed to produce an acceptable surface finish.

Experimental Procedures

The purpose of this work was to compare different surface finishing techniques for smoothing the ridged layer-additive surface finish of parts fabricated using the EBF³ process. Five pylons were fabricated from 0.063 in. diameter aluminum alloy 2219 (Al-6% Cu nominal composition) wire using the EBF³ process. The pylons were each 4.5 in. long, 1.5 in. wide, and 2 in. high with a wall thickness of approximately 0.25 in. A pylon in the as-built condition is

shown in Figure 1. The pylons were used to demonstrate finishing techniques on a contoured component. A straight wall was also built 10 in. long, 2 in. high, and approximately 0.25 in. thick. This straight wall was cut into five 2-in. long segments, which were subjected to the same finishing treatments as the pylons. These wall segments were used for residual stress and surface finish measurements and then were sectioned for metallurgical analysis. Since all of the wall segments came from the same build, comparing data on these straight wall segments was a direct measure of the surface treatments and was not influenced by any inconsistencies that may occur in the EBF³ fabrication process from part to part. The deposition rate for the pylons and the straight wall was approximately 12 in.³/hr, resulting in a build time of 6 hr. per pylon.

The surface treatments evaluated were: high speed milling, wire electrical discharge machining (EDM), glass bead blasting, and electron beam glazing. A brief description of the conditions used for performing these surface finishing operations follows. These surface treatments were compared to the as-built condition based on an evaluation of the surface roughness and waviness, surface residual stress state imposed into the part, and the impact of the surface treatment on the near-surface microstructure.

High Speed Milling

Figure 2 shows a pylon after high speed milling on the inside and outside surfaces. A 0.500-in. diameter, 4 flute, high speed steel end mill was used to remove approximately 0.01-0.02 in. from each surface at a feed rate of 15 in./min. The machining operation consisted of two passes, a roughing pass and a finishing pass, and took approximately 4 min. of actual machining time. The pylon solid model developed for the EBF³ system was also used to program the machining, so minimal time was required to program the milling operation. However, additional time was spent: (1) removing the part from the EBF³ system, (2) setting up the pylon in the high speed milling machine, and (3) positioning the near-net shape part with respect to the machining file to perform the machining. Similar machining set-up and feed rates were also used to cut the 2-in. straight wall segment down the centerline of the deposit for analysis. The operator reported that the machinability of the EBF³ material was comparable to typical aluminum.

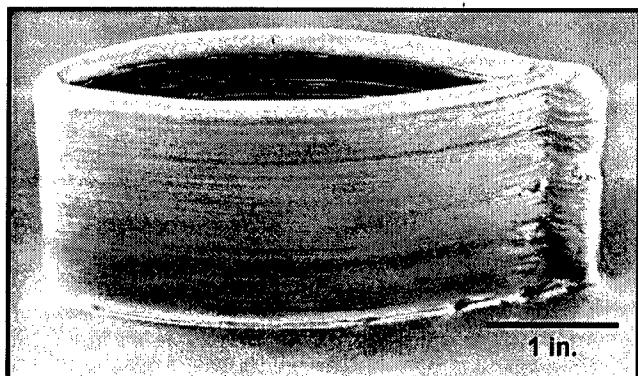


Figure 1. Electron beam freeform fabricated 2219 Al pylon in as-built condition.

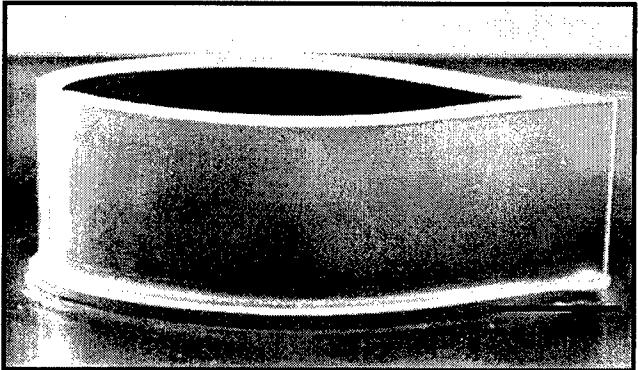


Figure 2. Electron beam freeform fabricated 2219 Al pylon after high speed milling.

Wire EDM

Figure 3 shows a pylon after being separated from the baseplate and wire EDM on the inside and outside surfaces. A 0.010 in. diameter wire was used to EDM the pylon. Actual wire EDM time was approximately 10 min. to remove approximately 0.05 in. from the inside and outside of the pylon. Prior to machining the pylon surfaces, a pilot hole was drilled into the baseplate in the center of the pylon because the wire must pass through the part to carry the current during wire EDM, preventing wire EDM from being effective for plunge operations. In addition, supports were left on either side near the center of the pylon to avoid pinching the wire. (The remnants of these supports are still visible as vertical stripes in Figure 3.) These supports were then removed in a subsequent machining operation. As with the high speed milled pylon, the pylon solid model developed for the EBF³ system was also used to program the wire EDM system, minimizing programming time. However, additional time was spent: (1) removing the part from the EBF³ system, (2) setting up the pylon in the wire EDM, (3) positioning the near-net shape part with respect to the machining file to perform the machining, and (4) final removal of the supports. Although wire EDM is typically followed by a grinding operation to remove the rough recast layer, the recast layer was not removed from the pylon to enable surface finishing analysis. Similar power settings and feed rates were also used to cut the 2-in. straight wall segment down the centerline of the deposit for analysis. Aside from the additional steps required for the wire EDM process, the operator reported no problems with machining the parts fabricated using the EBF³ process.

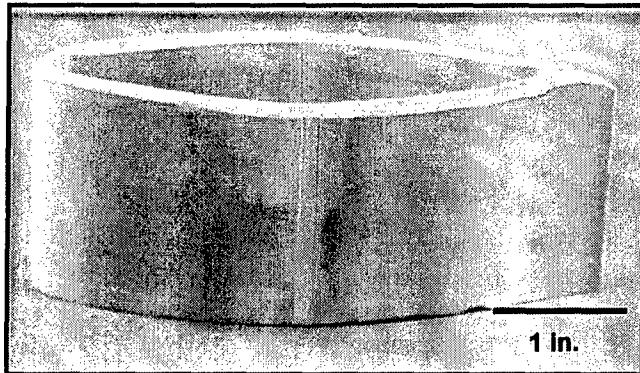


Figure 3. Electron beam freeform fabricated 2219 Al pylon after wire EDM machining.

Glass Bead Blasting

Figure 4 shows a pylon after glass bead blasting the exterior surface of the pylon. The pylon was bead blasted for 4 min. at a feed rate of approximately 5 in./min. using 0.015 in. diameter glass bead media. The set-up time was minimal since the bead blasting was manually controlled. Due to the geometry of the pylon, it was not possible to reach the inside surfaces of the pylon effectively. The 2-in. straight wall segment was bead blasted on both surfaces using feed rates and times similar to those used for the pylon.

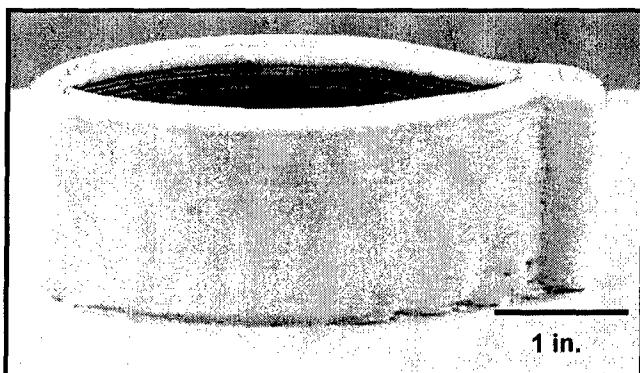


Figure 4. Electron beam freeform fabricated 2219 Al pylon after glass bead blasting.

Electron Beam Glazing

Figure 5 shows a pylon that was electron beam glazed in the EBF³ system immediately after completing the fabrication. The pylon was tilted 90° from the build orientation, and a low power, defocused electron beam was rastered perpendicular to the build direction to remove the EBF³ surface features. Total processing time was approximately 5 min., but no additional set-up time was required to perform the glazing operation. However, only the external surface of the pylon was accessible to the electron beam during the glazing operation, so it was not possible to reach the inside surfaces of the pylon effectively. Since the straight wall had to be removed from the EBF³ system to be cut into 2-in. segments, the 2-in. segment was returned to the EBF³ system and electron beam glazed using beam power and rastering rate and pattern similar to those used for the pylon.

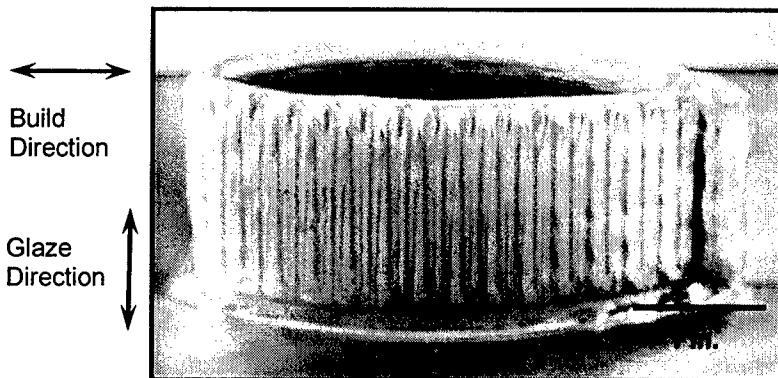


Figure 5. Electron beam freeform fabricated 2219 Al pylon after electron beam glazing.

Microstructural Analysis

Cross sections of the 2-in. straight wall segments were polished and etched with Keller's reagent. The near-surface microstructures of the wall segments subjected to surface treatments were compared to that of the 2-in. straight wall segment in the as-built condition. The segments were photographed using an optical metallograph to examine the impact of the surface treatments on the microstructure of the segments.

Surface Roughness and Waviness

Surface roughness and waviness measurements were made on the 2-in. straight wall segments for each surface treatment investigated, and compared to the as-built condition. Surface roughness measurements were taken using a laser interferometer with a diamond stylus. The sensitivity of the measurements on the instrument used was +/- 0.1 μ m. Measurements of the root mean square (RMS) surface finish were taken over a distance of 0.09 in., measured across the layers (normal to the baseplate on which the part was fabricated) at a location in the center of the 2-in. build height. However, since a standard RMS finish measurement is highly localized, the surface waviness was also measured. Surface waviness measurements were made using the same laser interferometer over a 1.0 in. length across the layers, starting approximately 0.5 in. above the baseplate.

Surface Residual Stress

The surface residual stress state was measured on the center of the 2-in. straight wall segments for each surface treatment investigated, and compared to the as-built condition. The x-

ray diffraction method for measuring residual stresses is appropriate for assessing the surface residual stress state imparted by the different surface treatments because it measures residual stresses in a very shallow volume of material. The d vs. $\sin^2\psi$ technique [1] uses the displacement of atomic planes as an internal measurement of macro residual stresses near the surface of the specimen. The residual strain was determined by measuring the d -spacings of grains oriented at a variety of different angles with respect to the surface normal. The stress was then calculated from this measured residual strain using the bulk modulus of elasticity for 2219 Al. The experiments were performed using copper $K\alpha$ radiation, in which the depth of penetration in the aluminum specimens was $0.4 \mu\text{in}$. Measurements were taken over an area of approximately $0.25 \text{ in.} \times 0.25 \text{ in.}$ square at a location in the center of each straight wall segment. Residual stresses were measured in three orientations: parallel to the build direction (designated 0°), perpendicular to the build direction (across the layers, designated 90°), and 45° to the build direction (designated 45°).

Results and Discussion

Low and high magnification optical microstructures of the near-surface regions on each of the straight wall segments are shown in Figures 6-10 for the as-built, high speed milled, wire EDM, glass bead blasted, and electron beam glazed specimens respectively. In the as-built specimen, two deposit layers and the remelted zone between those two layers are evident in Figure 6a. The localized surface is quite smooth, but there is evidence of longer range periodic surface waviness corresponding to the layer height, which is approximately 0.03 in. for the parts fabricated in this study. The surface microstructure shown in Figure 6b is typical of the through-thickness microstructure, showing relatively large grains with some evidence of a solidification dendrite structure within the grains. After high speed milling, Figure 7a shows scallops on the bottom of the end mill cut, but the sidewall of the machined segment is smooth with no evidence of surface variations. Figure 7b shows that the grain structure of the 2219 Al was not affected by the milling. After wire EDM, there is no longer any evidence of long range surface waviness in Figure 8a. Figure 8b shows that the recast layer is less than $200 \mu\text{in.}$ thick, but this layer causes asperities on a fine scale. After glass bead blasting, Figure 9a shows the long range waviness associated with the prior build layers remains intact. In addition, localized surface roughness in Figure 9b appears higher than that of the as-built segment in Figure 6b. Finally, after electron beam glazing, the surface appears very smooth with no long range waviness in Figure 10a. More noticeable is the fine-grained, equiaxed microstructure at a constant 0.04 in. depth associated with the heat affected zone from the glazing pass. The microstructure in the near-surface region after electron beam glazing (Figure 10b) is much finer than that of the as-built microstructure in Figure 6b.

The micrographs qualitatively indicate the roughness of the as-built surface as compared to that resulting from the various surface treatments. Surface roughness and waviness measurements were taken on the same straight wall segments as photographed in Figures 6-10. These results are shown in Table 1 and Figure 11. Note that lower RMS values are associated with smoother surface finishes, with a mirror surface typically having an RMS value less than 8.

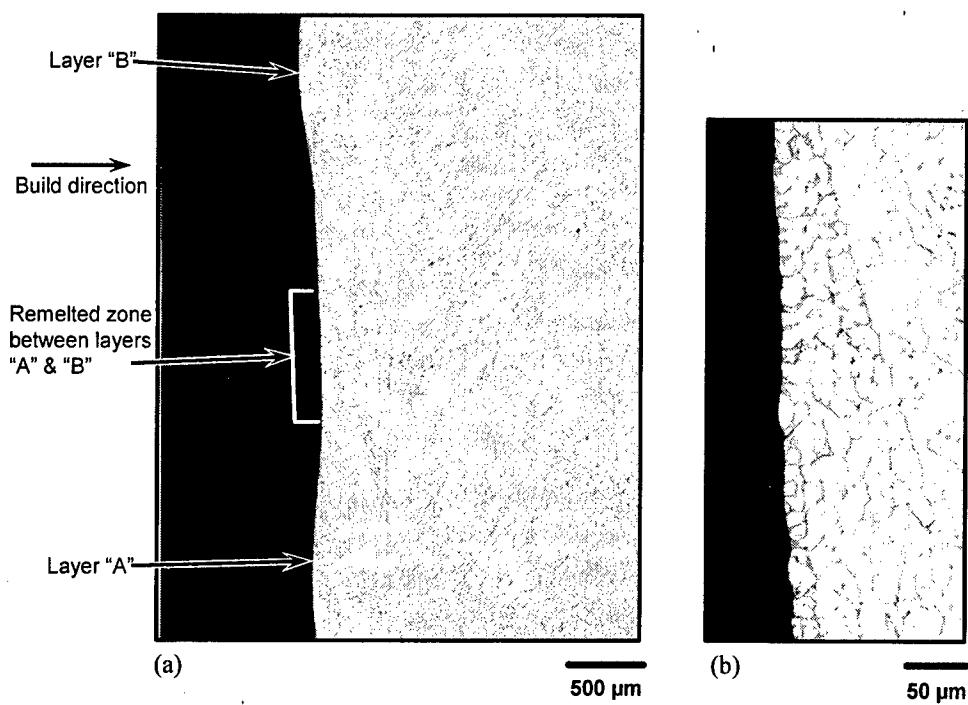


Figure 6. Microstructure of as-built electron beam freeform fabricated straight wall segment showing (a) long range waviness, and (b) surface microstructural details.

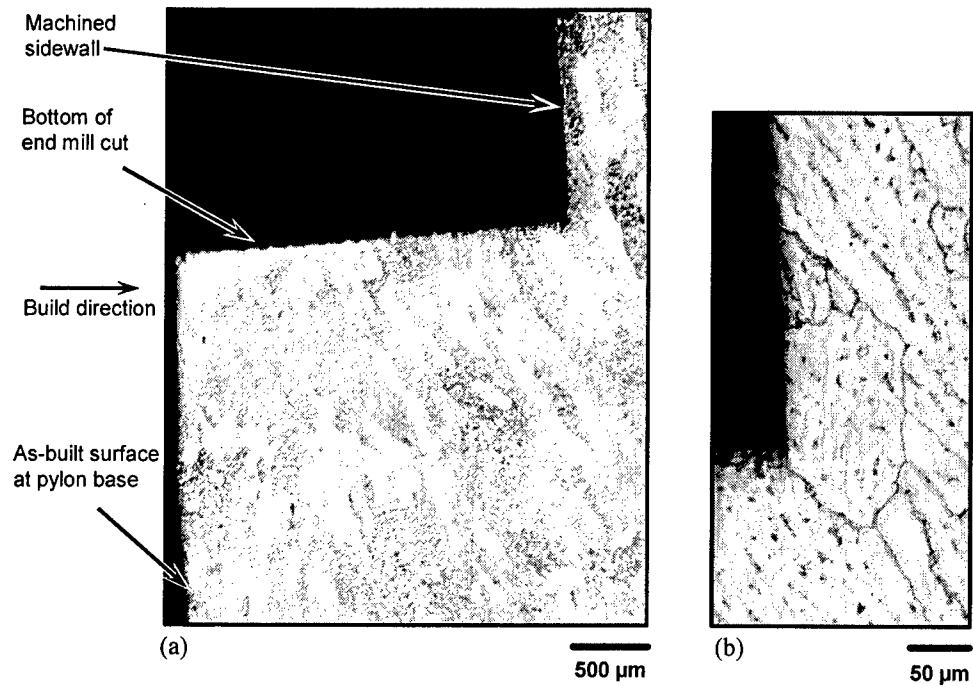


Figure 7. Microstructure of electron beam freeform fabricated straight wall segment after high speed milling showing (a) no long range waviness, and (b) uninterrupted surface microstructure.

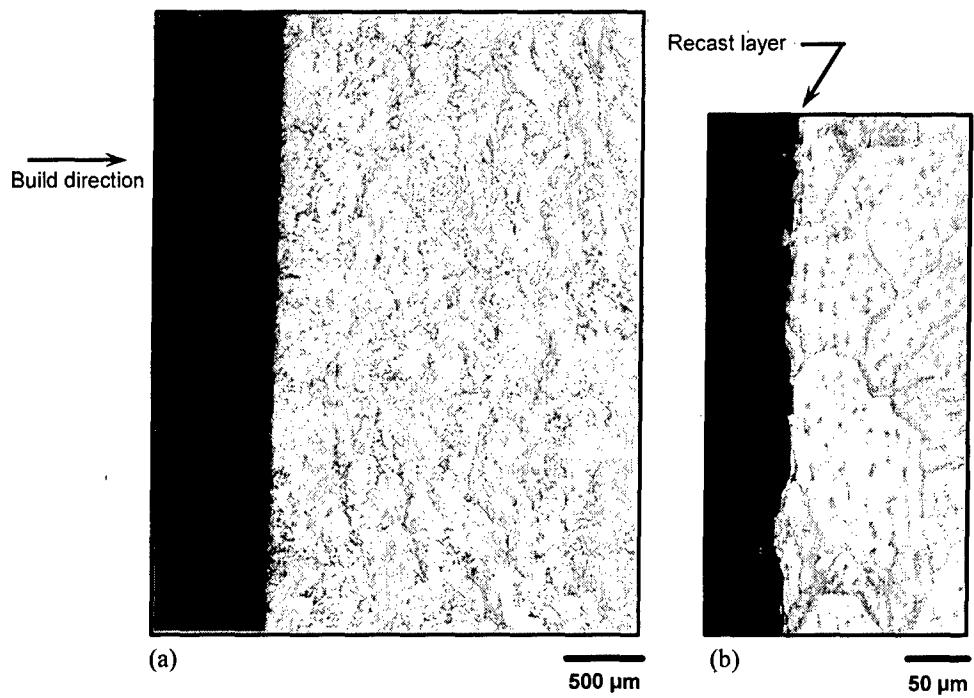


Figure 8. Microstructure of electron beam freeform fabricated straight wall segment after wire EDM showing (a) no long range waviness, and (b) recast layer on surface.

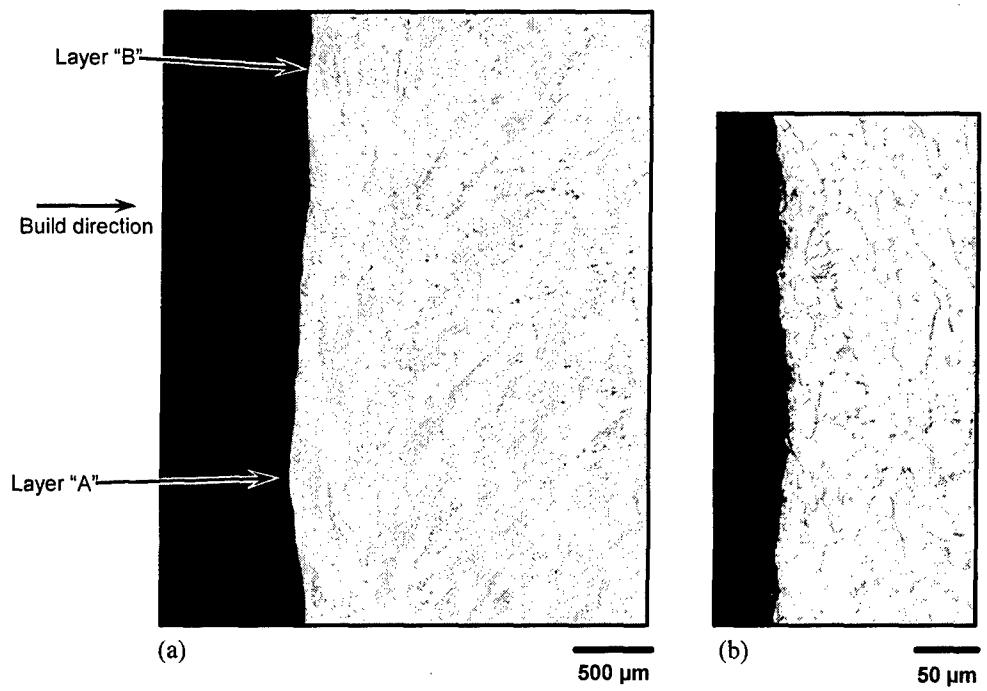


Figure 9. Microstructure of electron beam freeform fabricated straight wall segment after glass bead blasting showing (a) long range waviness and (b) surface roughness.

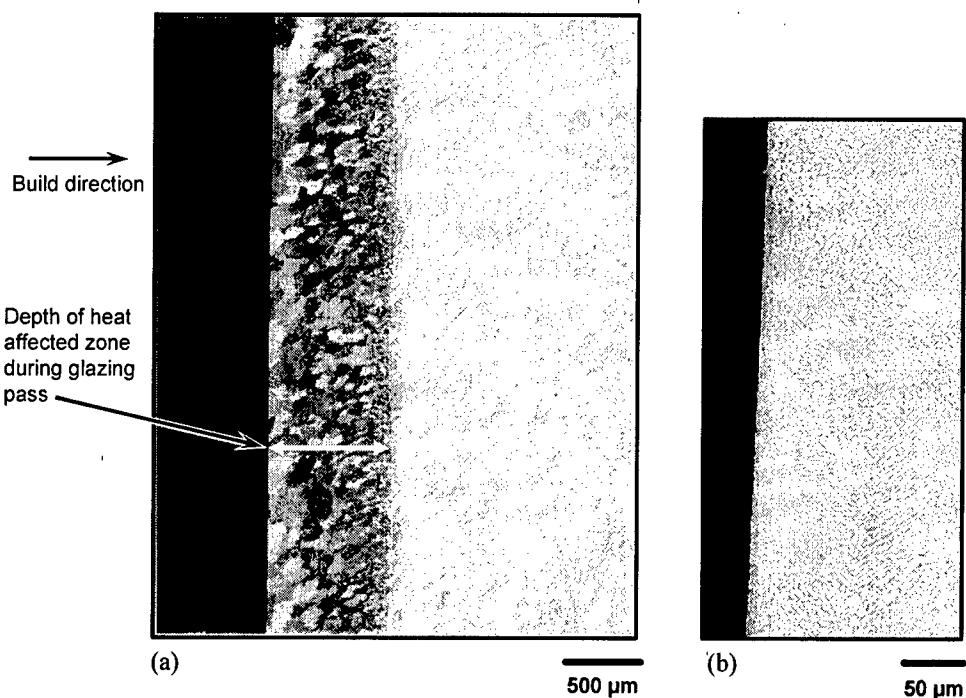


Figure 10. Microstructure of electron beam freeform fabricated straight wall segment after electron beam glazing showing (a) smooth surface with heat affected zone and (b) fine, equiaxed, near-surface microstructure.

Table 1. Surface roughness measurements for as-built and surface treated EBF³ deposits.

| Surface Treatment | RMS Roughness (µin.) | Waviness (µin.) |
|----------------------|----------------------|-----------------|
| As-built | 92 | 30,000 |
| High Speed Milled | 8-56 | 400 |
| Wire EDM | 196 | 1,500 |
| Bead Blasted | 233 | 12,000 |
| Electron Beam Glazed | 18 | 4,000 |

As the values for the as-built straight wall segment show in Table 1, it is possible to achieve a relatively low RMS surface finish yet have very high long range waviness. The as-built electron beam freeform fabricated segment has a reasonably low surface finish RMS value due to the smooth nature of the solidification of the molten pool. However, the layers result in a very high measure of waviness. Of the surface treatments studied, the electron beam glazed part produced the lowest RMS value, challenged only by high speed milling. The surface finish range shown for the milling machined specimen represents a range of surface finished achievable using this method – smaller step sizes can be applied to attain lower RMS values. Surface

asperities produced by the recast layer in the wire EDM machined segment and by the impact damage of the glass bead blasting actually increased the surface roughness RMS values versus the as-built segment.

In Figure 11, all of the waviness plots are shown on the same scale, providing direct comparison of the surface conditions resulting from each of the different surface treatments. All of the surface finishing techniques except for the glass bead blasting were successful at significantly reducing the surface waviness from the prior layers in the electron beam freeform fabricated segments. The periodicity of the slight waviness that remained in the electron beam glazed segment is associated with the width of the raster pattern used to perform the glazing operation.

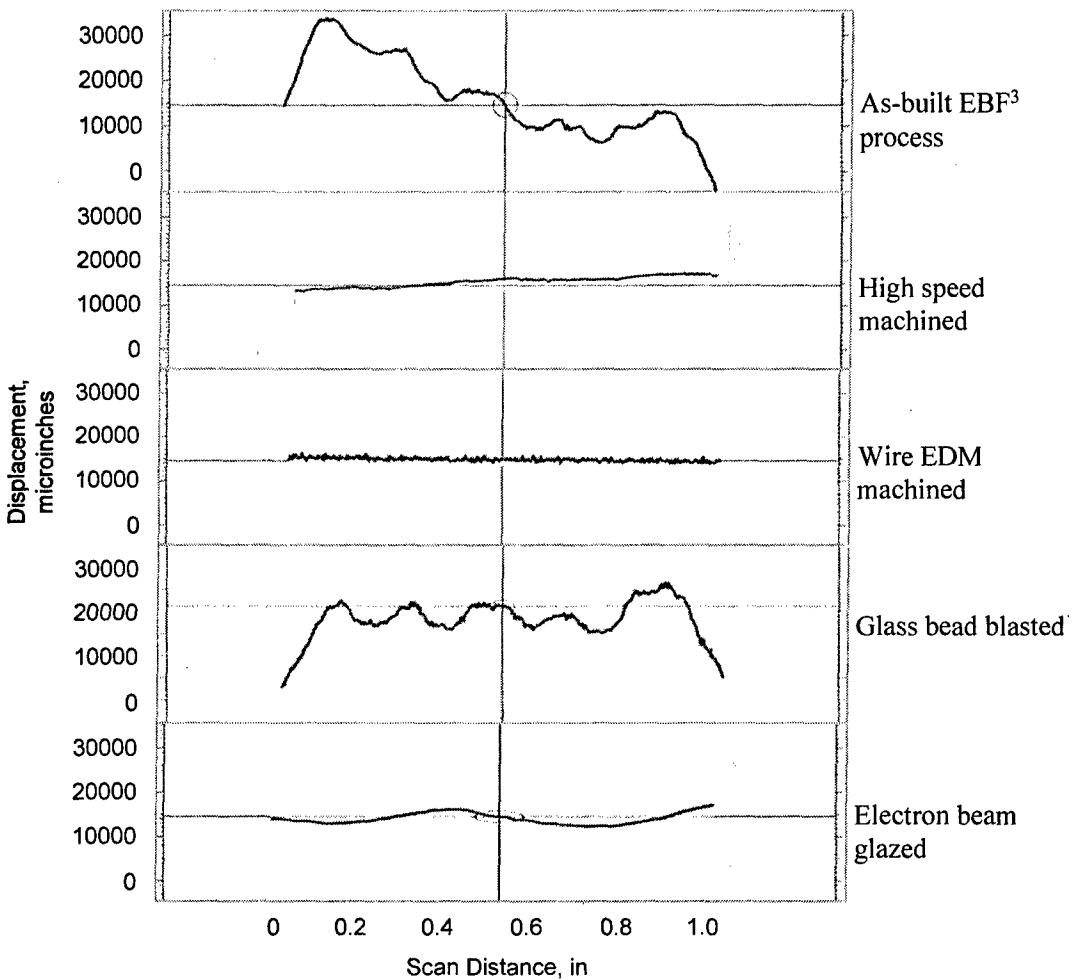


Figure 11. Surface waviness measurements on straight wall segments for each surface treatment studied.

Figure 12 shows the surface residual stress measurements from each straight wall segment parallel to the build direction (0°), perpendicular to the build direction (90°), and 45° to the build direction. The residual stresses are significant, but the magnitude of these values may not be accurate since the calculation of residual stresses is based upon the bulk tensile modulus

of the 2219 Al. There are two possible sources of error in the residual stress measurements shown in Figure 12. First, the modulus of the specific $\{hkl\}$ planes of atoms measured at the atomic scale should be used to convert from residual strain to residual stress using the x-ray diffraction method. Since atomic-level moduli are difficult to determine and generally unavailable, it is standard practice to use a bulk modulus value as a best approximation. [1] However, this assumption may not be very accurate. Second, the yield and ultimate tensile strengths of as-deposited 2219 Al are approximately 17 ksi and 40 ksi respectively. [2] Thus, this conversion is invalid for stresses exceeding the yield strength of the material. Therefore, when examining the measured residual stresses, the relative values are more important than the specific magnitudes shown.

The as-built segment exhibits moderate compressive residual stresses in the 0° orientation and low tensile residual stresses in the 45° and 90° orientations. These residual stresses are the result of thermal stresses, and are comparable to residual stresses expected from welding processes. [3] High speed milling, wire EDM, and glass bead blasting all induce compressive residual stresses in all directions. These measured results are consistent with handbook values for these finishing processes. [4] Electron beam glazing does not significantly change the compressive residual stress state in the 0° orientation or the tensile residual stresses in the 90° orientation versus the as-built segment. However, electron beam glazing does induce high compressive residual stresses in the 45° orientation as compared to the slightly tensile stresses measured in the as-built segment.

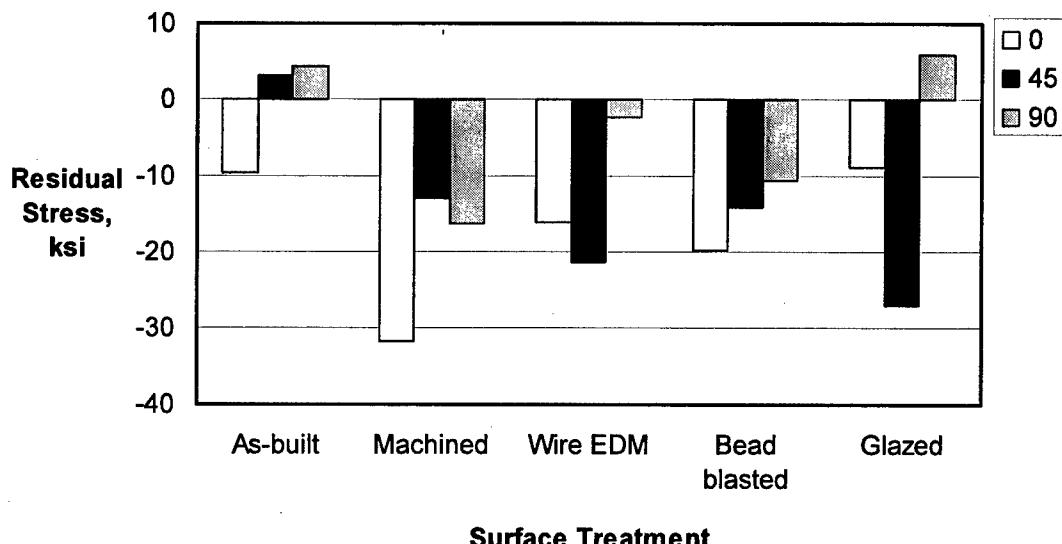


Figure 12. Surface residual stresses measured via x-ray diffraction on straight wall segments for each surface treatment studied.

Conclusions

- Electron beam glazing conducted in the EBF³ system is a viable process for removing surface waviness associated with EBF³ deposited layers, producing an RMS 18 surface finish with fine-grained equiaxed surface microstructure.
- The best combination of low localized RMS surface finish and minimal long range waviness was achieved using high speed milling machining.
- Flat and contoured electron beam freeform fabricated parts were successfully machined using high speed milling and wire EDM. Both processes induced compressive residual stresses into the parts as is typical for these processes.
- Glass bead blasting was not aggressive enough to eliminate the ridged surface finish resulting from the EBF³ process.

References

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